PORTLAND CEMENT ASSOCIATION
RESEARCH AND DEVELOPMENT LABORATORIES

Development Department · Bulletin D21

TESTS OF CONCRETE PAVEMENTS ON GRAVEL SUBBASES

By L. D. Childs and
J. W. Kapernick

U. I. C. C.
JAN 26 1976
LIBRARY

Printed from the Journal of the Highway Division,
Proceedings of the American Society of Civil Engineers,
Proc. Paper 1800, Vol. 84, HW3, October, 1958

Bulletins Published by the Development Department Research and Development Laboratories of the Portland Cement Association

D1 —"Influence of Soil Volume Change and Vegetation on Highway Engineering," by E. J. FELT.
Reprinted from *Twenty-Sixth Annual Highway Conference of the University of Colorado*, May, 1953.

D2 —"Nature of Bond in Pre-Tensioned Prestressed Concrete," by JACK R. JANNEY.
Reprinted from *Journal of the American Concrete Institute* (May, 1954); *Proceedings*, 50, 717 (1954).

D2A—Discussion of the paper "Nature of Bond in Pre-Tensioned Prestressed Concrete," by P. W. ABELES, K. HAJNAL-KONYI, N. W. HANSON and Author, JACK R. JANNEY.
Reprinted from *Journal of the American Concrete Institute* (December, Part 2, 1954); *Proceedings*, 50, 736-1 (1954).

D3 —"Investigation of the Moisture-Volume Stability of Concrete Masonry Units," by JOSEPH J. SHIDELER.
Published by Portland Cement Association, Research and Development Laboratories, Chicago, Illinois, March, 1955.

D4 —"A Method for Determining the Moisture Condition of Hardened Concrete in Terms of Relative Humidity," by CARL A. MENZEL.
Reprinted from *Proceedings, American Society For Testing Materials*, 55 (1955).

D5 —"Factors Influencing Physical Properties of Soil-Cement Mixtures," by EARL J. FELT.
Reprinted from *Bulletin 108 of the Highway Research Board*, p. 138 (1955).

D6 —"Concrete Stress Distribution in Ultimate Strength Design," by E. HOGNESTAD, N. W. HANSON and D. MCHENRY.
Reprinted from *Journal of the American Concrete Institute* (December, 1955); *Proceedings*, 52, 455 (1956).

D6A—Discussion of the paper "Concrete Stress Distribution in Ultimate Strength Design," by P. W. ABELES, A. J. ASHDOWN, A. L. L. BAKER, ULF BJUGGREN, HENRY J. COWAN, HOMER M. HADLEY, KONRAD HRUBAN, J. M. PRENTIS, E. ROSENBLUETH, G. M. SMITH, L. E. YOUNG, A. J. TAYLOR, and AUTHORS, E. HOGNESTAD, N. W. HANSON, and D. MCHENRY.
Reprinted from *Journal of the American Concrete Institute* (December, Part 2, 1956); *Proceedings* 52, 1305 (1956).

D7 —"Ultimate Flexural Strength of Prestressed and Conventionally Reinforced Concrete Beams," by J. R. JANNEY, E. HOGNESTAD and D. MCHENRY.
Reprinted from *Journal of the American Concrete Institute* (February, 1956); *Proceedings*, 52, 601 (1956).

Continued on Inside Back Cover

Paper 1800 October, 1958 HW 3

Journal of the
HIGHWAY DIVISION
Proceedings of the American Society of Civil Engineers

TESTS OF CONCRETE PAVEMENTS ON GRAVEL SUBBASES

L. D. Childs[1] and J. W. Kapernick[2] J.M. ASCE
(Proc. Paper 1800)

SYNOPSIS

Concrete pavement slabs 8 in. by 12 ft by 18 ft joined by 1-in. round dowels were subjected to static loads to study the effect of various thicknesses of open-graded sand and gravel subbases upon the strength of the composite pavement structure. Deflections and strains in the concrete and pressures on the subbase and subgrade were measured for eight load positions when the slab was flat and when it was curled upward at corners and edges.

This is the second phase of a comprehensive study which is concerned primarily with subbases and secondarily with slab deflections and stresses and with interface pressures. Where load conditions permitted comparisons, it was found that trends reported in the first phase in testing 6-in. slabs on dense-graded sand and gravel subbases(1) were supported by the present study, although magnitudes were affected by subbase material and slab dimensions.

The present experiments showed that open-graded sand and gravel subbases under flat slabs were more effective in reducing free-corner and free-edge deflections than in reducing strains. Computations based upon the test data and a theoretical treatment showed that under free-corner loads the deflection of an 8-in. slab on a 7.5 in. subbase would be about equal to that for a 9-in. slab with no subbase. However, a subbase 17 in. thick would hold corner strains in an 8-in. slab equal to those in a 9-in. slab with no subbase. Under edge loads the subbases were less effective in reducing deflections and strains than under corner loads.

Note: Discussion open until March 1, 1959. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. Paper 1800 is part of the copyrighted Journal of the Highway Division, Proceedings of the American Society of Civil Engineers, Vol. 84, No. HW 3, October, 1958.

1. Senior Development Engr., Transportation Development Section, Portland Cement Assn., Chicago, Ill.
2. Field Engr., Miller-Warden Associates, Chicago, Ill. Formerly, Associate Development Engr., Transportation Development Section, Portland Cement Assn., Chicago, Ill.

Deflections and strains for loads at doweled corners of flat slabs were reduced to 60% and 70%, respectively, of corresponding values at free corners. A load 1 ft inward transversely from the free corner position further reduced deflections to 40% of the free corner value. A load 1 ft inward from the free edge reduced both deflections and strains to 70% of the free edge value.

Pressures between the slab and subbase increased with subbase thickness but pressures on the subgrade diminished slightly as subbase thickness increased. Subgrade pressures under typical pavement loads were of the order of 5 to 6 psi for extreme edge loads and 2 to 3 psi for interior loads.

Experimental deflections and strains for interior, edge, and corner loads were compared with theoretical curves based upon the liquid subgrade hypothesis. Both deflections and strains obtained under interior loads on curled and flat slabs were slightly greater than those computed by Westergaard's 1926 or 1947 equations. Test deflections and strains at edges due to edge loads were close to those computed from Westergaard's 1947 equations for both flat and curled slabs. Under free corner loading the test deflections for flat slabs were in good agreement with Westergaard's 1926 equation but were greater than indicated by theory for curled slabs. Test strains near corners were between those computed by the 1926 equation and Pickett's equation when the slabs were flat but were in better agreement with the latter when the slabs were curled.

INTRODUCTION

Frequent heavy loads on concrete highways have revealed construction requirements which were not readily apparent under the lighter traffic prior to 1940. In some areas where traffic exceeded that for which the road was designed, pavements have developed faulted joints and structural cracks, frequently preceded by edge or joint pumping which contributed to a loss of subgrade support.

The need for a uniform foundation of reasonably constant bearing value became evident, and subbases were specified in new construction on fine-grained soils. These were generally of granular material and were either dense-graded to prevent concentrations of free water from reaching the subgrade, or open-graded to allow drainage to the side ditches.

Benefit from subbases was obtained in most cases. Roads built in areas where the native subgrade was clay or silt were greatly improved. The use of granular subbases, however, introduced problems of gradation, thickness, and method of placement of subbase materials to prevent faulting and pumping. The extent of the structural contribution made by subbases of different thickness to the pavement structure was also an important factor. Hence a comprehensive study on subbases was begun at the Portland Cement Association Laboratories.

Scope of the Program

This investigation is designed to study the effects of several types and thicknesses of subbase material on the load-carrying characteristics of concrete slabs. Tests are made on full-scale slabs on subbase materials and thicknesses which include those in actual use under concrete pavements. The

first phase of this study on dense-graded sand and gravel subbases has been completed and reported.(1) A second phase on open-graded sand and gravel subbases is reported in this paper, and tests are now in progress on open- and dense-graded crushed stone. These will be followed by an investigation of cement-treated materials. The studies will provide information on the effect of gradation, permeability, particle shape, and cement treatment.

The tests reported here are on 8-in. thick concrete slabs built on subbases 5, 10 and 15 in. thick constructed on a silty clay subgrade soil. Evaluation procedure involves observations of slab strains and deflections and subbase and subgrade pressures when static loads are applied to the paving slab. Control is maintained over slab thickness, subbase thickness, subgrade thickness, temperatures, subbase and subgrade moistures and densities, and slab shape (flat or curled upward at corners and edges).

Specific Objectives

The objectives of the program are:

1. To determine the effect of thickness of subbase on the load carrying characteristics of the slab.

2. To investigate the effect of subbases in distributing pressures to the subgrade.

3. To obtain information helpful in establishing relationships between slab thickness and subbase thickness to effect economy in design.

4. To compare experimental load-strain-deflection relationships with those computed in accordance with the theory that deflection is everywhere proportional to pressure, as in the Westergaard theory.

Facilities and Materials

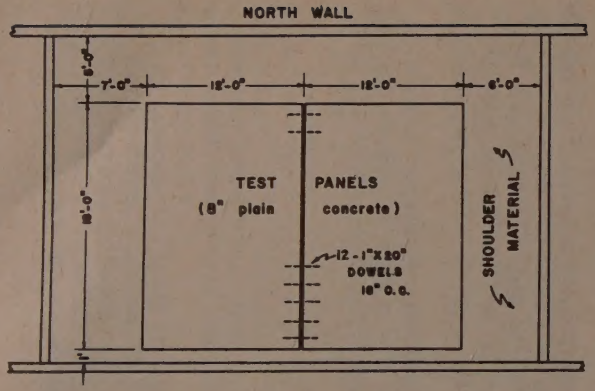
Tests are conducted in a 24- by 37-ft waterproofed reinforced concrete pit described in the first report.(1) The test pit was filled to a depth of 4 ft with well compacted silty clay. Subbases 5 in., 10 in., and 15 in. thick were built upon the clay subgrade and pairs of doweled 12- by 18-ft by 8-in. plain concrete slabs were cast upon the subbases. Fig. 1 shows the plan and profile of the installation.

Static loads were applied by hydraulic jacks reacting against an overhead frame. An overall view is shown in Fig. 2. The reinforced concrete building in which the tests were made was heated to permit year-round activity with temperature control.

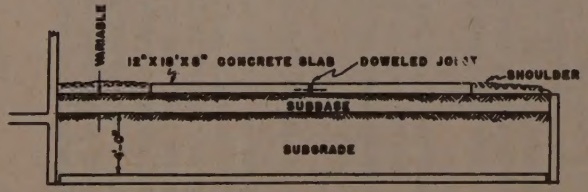
Subgrade and Subbase Materials

Table 1 presents gradation and physical properties of the clay subgrade soil and of the sand and gravel subbase. Moisture-density and CBR-moisture relationships are shown in Fig. 3.

The subgrade soil was spread upon a concrete apron and prepared for placement by working it with a rotary tiller at a moisture content slightly above optimum. It was placed in 6-in. lifts and compacted with tamping rammers. Bearing plate tests and in-place density and moisture tests were made on one-foot layers for control. Fig. 4 shows the bearing values on top of the



— PLAN —



— ELEVATION —

LAYOUT OF TEST PANELS

Fig. 1

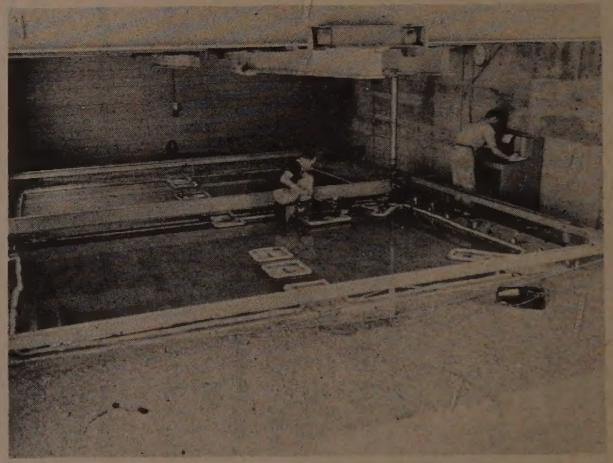


Fig. 2 Overall View of Test Area. Slabs flooded to prevent upward curl due to surface drying.

TABLE 1

GRADATION AND SOIL LIMITS OF SUBGRADE AND SUBBASE MATERIALS

GRANULAR SUBBASE		CLAY SUBGRADE	
Gradation			
Sieve	**% Passing**	**Particle Size**	**%**
1"	100	Coarse Sand (2.0 - 0.42 mm)	6
3/4"	98	Fine Sand (0.42 - 0.074 mm)	8
3/8"	85	Silt (0.074 - 0.005 mm)	48
#4	68	Clay (below 0.005 mm)	38
#10	43	Colloids (below 0.001 mm)	30
#40	12		
#200	2		
Soil Constants			
Non Plastic		Liquid Limit	36
		Plasticity Index	19
Moisture-Density Relationships, AASHO T 99			
Maximum Dry Density*	135 PCF	Maximum Dry Density	112 PCF
Optimum Moisture*	7.3%	Optimum Moisture	16.2%

*Includes No. 4 to 1" aggregate in the test specimen

subgrade at 0.05 in. deflection for plates having diameters of 12, 16.6, 24, and 30 in. Westergaard's subgrade modulus k, determined with a 30-in. plate, was 75 pci.

The subbase material was a bank-run sand and gravel which had been run through a crusher to hold the maximum size to 1 in. The material was placed in lifts and vibrated to the required density. The full 15-in. thickness was placed and tested first, and the thickness was reduced to 10 in. and to 5 in. by cutting off the top layers for the second and third tests. After cutting, some reworking of the subbase surfaces was necessary for fine grading to obtain uniform slab thickness. Plate bearing values on all three subbase thicknesses are shown in Fig. 4. Westergaard's modulus k for each subbase thickness is given in Table 3.

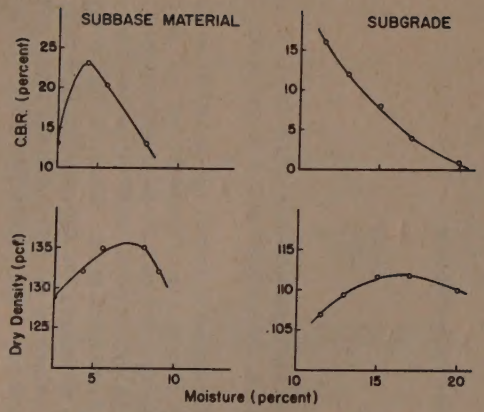


Fig. 3 - M-D AND CBR RELATIONS

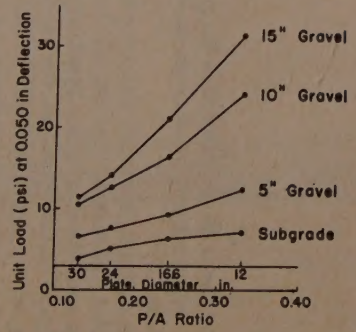
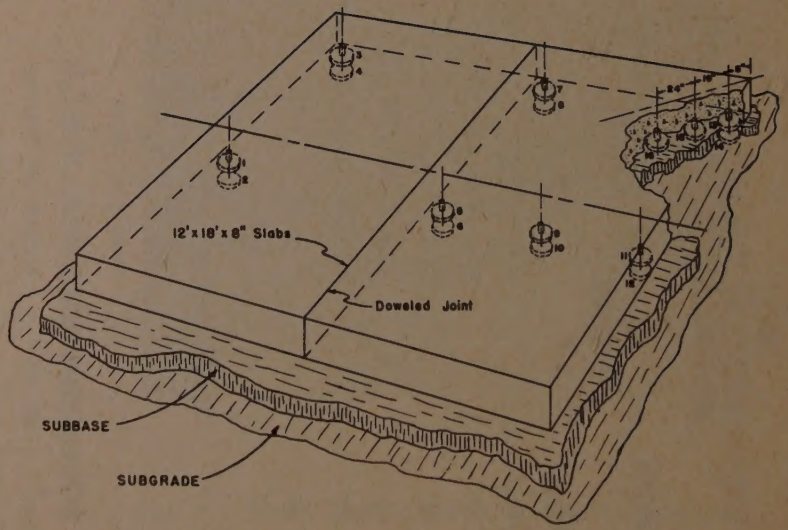


Fig. 4 - FOUNDATION BEARING VALUES



Cells 1,3,5,...etc. between slab and subbase
Cells 2,4,6,...etc. between subbase and subgrade

PRESSURE CELL LOCATIONS

Fig. 5

Concrete Pavement Panels

The pavement for each test included two 12-ft by 18-ft by 8-in. panels separated by a 3/16 in. joint with sheet metal full-depth parting plate and doweled along the 18-ft edge by 1- by 18-in. slip dowels on 18-in. centers. The dowels established deflection continuity across the joint. The joint construction also permitted a comparison of strains, deflections, and pressures at the outer boundaries of the slab with those in the area of dowel restraint.

The concrete, mixed in the laboratory, had a cement factor of 6 sk per cu yd, a water-cement ratio by weight of 0.50, a slump of 3 in. and an air content of approximately 5%. The properties of fog-cured test specimens are given in Table 2.

TABLE 2

CONCRETE PROPERTIES

Slab Foundation	Age Days	Strength - psi Cylinder Compression	Strength - psi Beam Flexure	Dynamic E Million psi Cylinder	Dynamic E Million psi Beam
	7	3400	530	4.5	4.5
Clay	14	4000	590	4.7	4.8
	28	4600	650	4.9	5.2
	7	4400	500	4.3	4.8
5"	14	5200	580	4.7	5.2
Subbase	28	5500	640	5.2	5.4
10"	14	4800	660	5.4	5.3
Subbase	28	5700	700	5.6	5.6
15"	28	4500	620	4.7	4.8

The test slabs were cured 7 days under wet curlap, then ponded until the loading tests for the flat slabs were completed. At the end of this period, usually 5 to 6 weeks, the water was removed, the slabs were permitted to dry from the top and the load tests were repeated on the curled slabs.

Instrumentation

Instruments for the measurement of strain, deflection, and pressure were the same as described in the previous report,(1) namely, SR-4 type A-9 bonded strain gages on the slab surface, 0.001-in. dial indicators attached to

a wooden bridge for deflection measurement, and Carlson stress meters for pressure indication. Pressure cell and strain gage locations are shown in Figs. 5 and 8 respectively.

In addition to deflections due to loads, the vertical deformations of the slabs due to drying shrinkage were measured. For this purpose a loose-pin deflectometer was used. This permitted readings of slab position at any time without the necessity of a permanent dial installation at each measuring point. The deflectometer is illustrated in Fig. 6. The brass housing was attached to a reference rod driven into the subgrade, and the loose pin rested upon a target on the slab surface. The dial indicator equipped with an adapter measured the change in the distance from the top of the pin to the machined face of the brass housing.

Test Details

Bearing plate tests were made upon the subgrade before and after completion of the tests on subbases, and at four locations on each subbase. The average k value and associated in-place moisture and in-place density for each subbase thickness are given in Table 3.

TABLE 3

IN-PLACE TESTS ON SUBGRADE AND SUBBASES

Subbase Thickness in.	In-Place Dry Density pcf	Moisture Content %	k from 30" Plate 0.05" Deflection pci
0*	111	20.0	75
5	132	4.6	130
10	137	4.7	200
15	135	4.9	225

* Tests on Subgrade

Static loads on the slabs were applied by hydraulic jack to a 12-in. diameter steel plate resting upon a firm rubber pad the same size as the plate. Load intensity was measured with Baldwin load cells and an SR-4 indicator. A typical test is illustrated in Fig. 7. Load tests were made at the following locations: free corner, doweled corner, free edge, doweled edge, interior, inward from the free corner, inward from the doweled corner, and inward from the free edge. The 8 load positions are shown in Fig. 8. The loads were applied in increments of 3,000 lb, and in most cases the maximum load was 15,000 lb. At position 1, maximum deflections were at the load and maximum tensile strains were assumed to be equal to the maximum measured compressive strains under the load. At positions 2, 5, and 6, maximum deflections were measured at the slab edge and maximum tensile strains were assumed to be equal to the maximum compression indicated by the gage at the slab edge. At positions 3 and 4 maximum deflections occurred at the

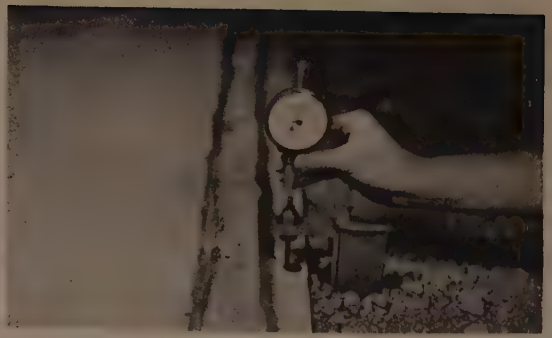


Fig. 6 Deflectometer for Measurement of Elevation Changes due to Curl.

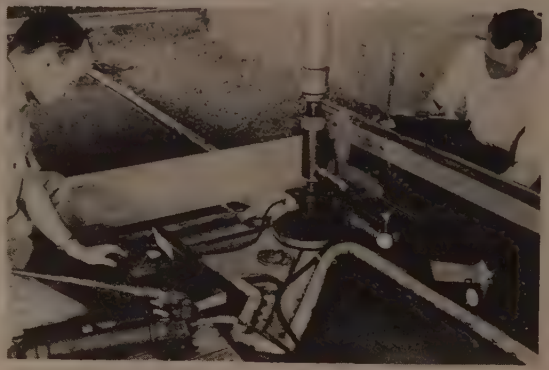
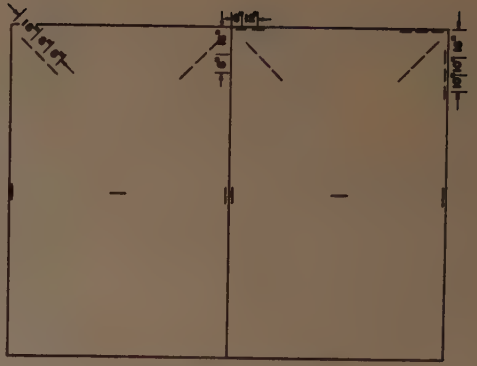
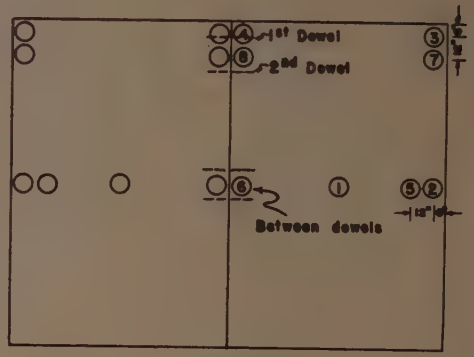


Fig. 7 Typical Load Test.



STRAIN GAGE LOCATIONS



LOAD POSITIONS

Fig. 8

corners. Maximum tensile strains were measured on the corner bisector at some distance inward from position 3, but were found to be along the doweled edge for position 4. For positions 7 and 8 maximum deflections occurred at the corners and the magnitude of compressive strains on the slab edges at the point of plate tangency exceeded that of any tensile strain along the slab edge or corner bisector. Hence maximum tensile strains were assumed to be of the same magnitude as the maximum compression strains measured at the slab edges.

The tests were made when the slab was in a flat state and when the slab edges and corners had curled upward due to drying at the top surface. The study of slab deflections and strains and foundation pressures was not as comprehensive for the curled condition as for the flat condition, but sufficient tests were made to illustrate the effect of upward curl upon these measurements.

Tests on Flat Slabs

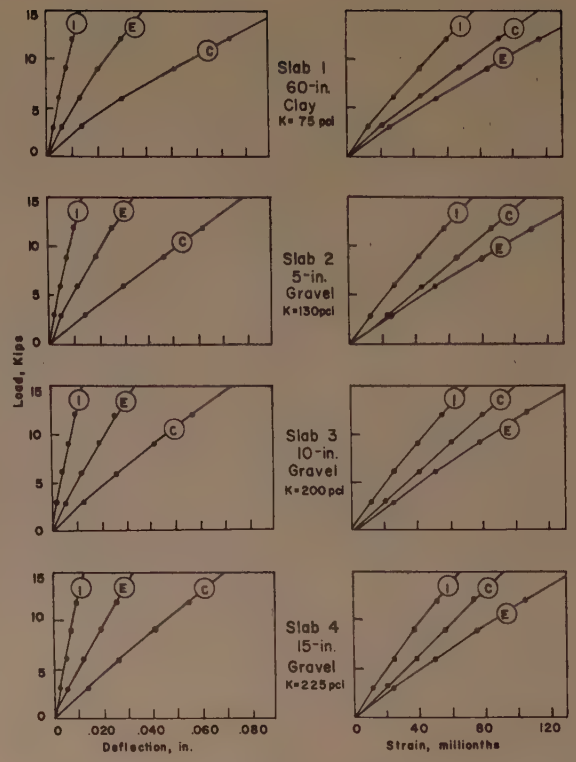
Maximum Deflection and Strain

Figs. 9, 10 and 11 present the measured strains and deflections for the 8 positions of load. It is seen in Fig. 9 that the relationships among interior, free edge, and free corner deflections and strains established in the previously reported tests(1) on 6-in. slabs with dense-graded subbases are maintained. Free corner deflections greatly exceed free edge deflections, but the maximum strain under edge loads exceeds the maximum strain produced by loads at the corners. At doweled edges and corners, as seen in Fig. 10, the deflections and strains are reduced but the relationship is the same as before, i.e., corner deflections exceed edge deflections and edge strains exceed corner strains.

As shown in Fig. 11, when loads are applied inward from the free edge, free corner, and doweled corner, free corners again deflect more than doweled corners and these in turn deflect more than free edges. However, there is a marked equalization in strains, and all strain curves are closely grouped.

The influence of load position upon deflections and strains in a flat slab for a 10,000-lb load is readily seen in Fig. 12. Only the data for the slabs on the 5-in. subbase are shown but the trend is the same for all subbases. The deflection at a loaded doweled corner is 57% of the deflection at a loaded free corner. If the load is inward one foot from the free corner the deflection of the corner is 70% of the value when the load is at the corner. When the corner is doweled and the load is 1 ft inward, the slab deflection is 40% of that for a load on the free corner. This value is the same as the relatively small deflection measured with the load at the free edge. Thus dowels alone restrain corner deflections appreciably and a combination of dowels and a load path 1 ft from the slab corner is very effective in reducing deflection.

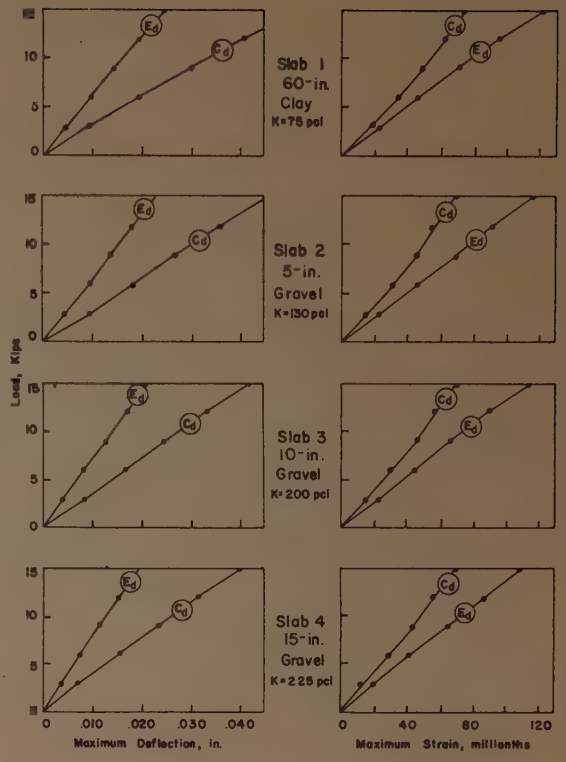
Strains are affected by dowels and load position to a lesser degree than deflections. When the load is at a free edge the strain is 21% greater than that due to a load at a free corner. Strain due to a load at a doweled edge is 16% less than that at a free edge, but still exceeds strain for a free corner load. When the load is 1 ft inward from the free edge, the maximum strain is 58% of the strain due to a free edge load. This maximum strain remains about the same when the load is 1 ft in from the edge at either a doweled or



Load at Interior (I) Free Edge (E) and Free Corner (C)

DEFLECTIONS AND STRAINS

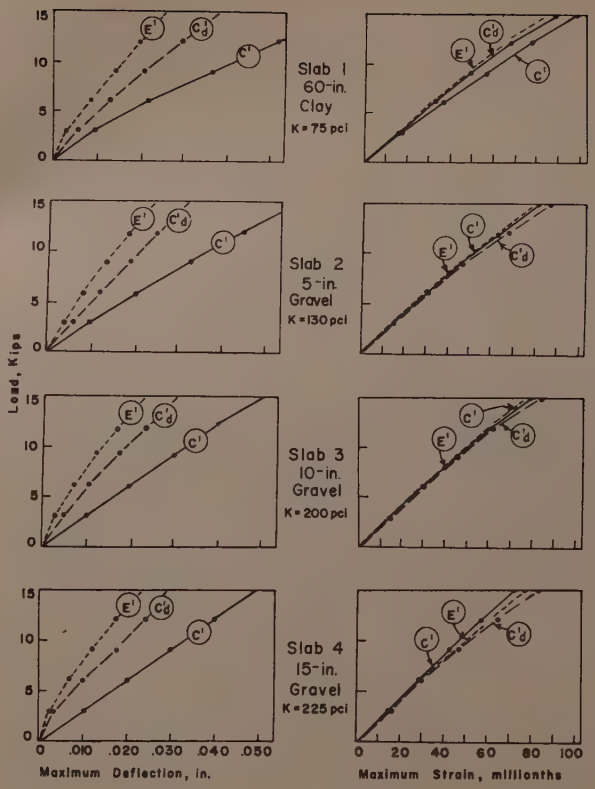
Fig. 9



Load at Doweled Edge (Ed) and Doweled Corner (Cd)

DEFLECTIONS AND STRAINS

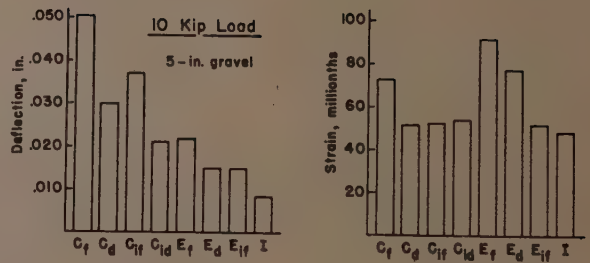
Fig. 10



Load inward 1 ft. from Free edge (E'), Free corner (C') & Doweled corner (C'd)

DEFLECTIONS AND STRAINS - LOADS 1 FT. INWARD

FIG. 11



Load Positions - C_f = Free Corner, C_{if} = Inward from Free Corner C_d = Doweled Corners, C_{id} = Inward from Doweled Corner, E_f = Free Edge, E_{if} = Inward from Free Edge, E_d = Doweled Edge, I = Interior

EFFECT OF LOAD POSITION ON DEFLECTIONS AND STRAINS

Fig. 12

free corner. The maximum strains developed by loads 1 ft inward from the free edge or corner of the slab are only slightly greater than those for an interior load. The effect of load position is significant and warrants consideration in pavement design.

Comparison with Theory

Several equations are available for computing theoretical stresses and deflections for comparison with the measured (experimental) values. The equations used are listed in Table 4. Numbers 1 through 6 were developed by Westergaard[2] in 1926. Numbers 7 and 8 are 1933 modifications by Westergaard. Kelley's[3] modification for edge stresses is equation 9 and Pickett's[4] formula for corner stresses is equation 10. Numbers 11, 12, 13 and 14 are Westergaard's 1947 equations.[5] The stresses computed by the various equations in Table 4 were converted to strains for direct comparison with experimental data. In making this conversion the biaxial effect resulting from loads at positions other than the extreme edge was considered.

Constants for stress and deflection computation are: $h = 8$ in., $r = 6$ in., $u = 0.15$, $E = 4{,}500{,}000$ psi, and $k = 75$, 130, 200 and 225 pci. The elastic modulus was not exactly 4,500,000 psi for all tests, but variations in E were minor and did not cause significant changes in computed stresses.

Charts comparing experimental and theoretical deflections and strains are shown in Figs. 13, 14, and 15. Generally, the experimental deflections and strains at the interior were slightly greater than those computed by theory. Westergaard's original equations gave a much better check than his 1933 modified equations. Lines representing the 1947 equations (11 and 12) would have been almost coincident with 1 and 2.

At the free edge, aside from low experimental deflections for the slab on clay, the experimental values matched theory very well. Experimental deflections agree closely with Equation 4 (Westergaard: 1926) and Equation 14 (Westergaard: 1947), while Equation 13 (Westergaard: 1947) agrees with experimental strains.

There is only one theoretical curve (Equation 6) for comparison with corner deflections, and experimental values check theory rather well except for slab 1. Experimental values of strains fall between the limits defined by equations 5 and 10, with Equation 5 having a slight advantage over 10. It is reasonable to expect that theoretical strains computed by equation 10 would exceed experimental values since this equation was developed for curled slabs.

For all load positions experimental deflections were less than theoretical for tests on the subgrade and greater than theory for the thicker subbases. This sensitivity to changes in k was not apparent in the strain data where the experimental values were always bounded by theoretical curves.

Influence of Subbase Thickness upon Deflections and Strains

Maximum experimental deflections and strains for a 10,000-lb load on 8-in. concrete panels on subbases of different thicknesses are plotted in Fig. 16A. The deflection curves have steepest slope in the segments 0 to 5 in. Free corner deflections are reduced 0.009 in. by a 5-in. subbase compared to 0.014 in. by 15 in. of subbase. Thus, 64% of the reduction is accomplished by a 5-in. subbase. At the edge, deflections were reduced 0.003 in. by the 5-in. subbase thickness, with no further reduction due to additional thickness of

TABLE 4

DESIGN EQUATIONS

(Circular Loading Area, Radius r)

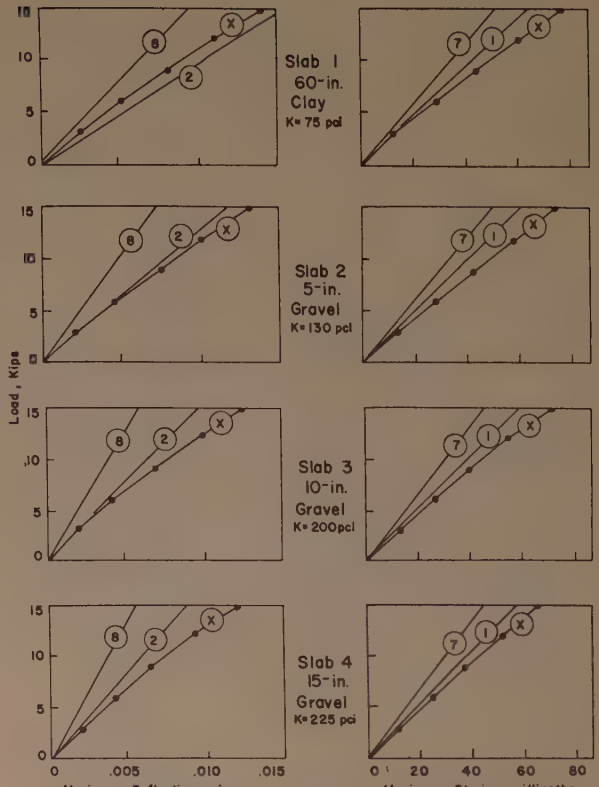
Load Position	Source and Date	Equation No.	Simplified Equation
			Maximum Stress, psi
Interior	W - '26	1	$S_i = S_1 = 0.275\ (1 + u)\ \frac{P}{h^2}\ (4 \log \frac{L}{B} + 1.069)$
Edge	W - '26	3	$S_e = 0.529\ (1 + 0.54u) \frac{P}{h^2}\ (4 \log \frac{L}{B} + 0.359)$
Corner	W - '26	5	$S_c = \frac{3P}{h^2} \left[1 - \left(\frac{r\sqrt{2}}{L}\right)^{0.6}\right]$
Interior	W - '33	7	$S_i = S_1 - 15\ (1 + u)\ \frac{P}{h^2} \left(\frac{L}{L_1}\right)^2\ Z$
Edge	K - '39	9	$S_e = 0.529\ (1 + 0.54u)\ \frac{P}{h^2}\ (4 \log \frac{L}{B} + \log B)$
Corner	P - '46	10	$S_c = 4.20\ \frac{P}{h^2} \left(1 - \frac{\sqrt{rL}}{0.925L - 0.22r}\right)$
Interior	W - '47	11	$S_i = 0.275\ (1 + u)\ \frac{P}{h^2}\ (4 \log \frac{L}{r} + 1.069)$
Edge	W - '47	13	$S_e = \frac{1 + u}{3 + u}\ \frac{P}{h^2} \left[8.80 \log \frac{L}{r} - \frac{1m}{\pi} - 0.290 + \frac{3}{\pi} \left(\frac{1 - u}{2} + 1.18\ (1 + 2u)\ \frac{r}{L}\right)\right]$
			Maximum Deflection, in.
Interior	W. - '26	2	$d_i = \frac{P}{8kL^2}$
Edge	W - '26	4	$d_e = 0.409\ (1 + 0.40u)\ \frac{P}{kL^2}$
Corner	W - '26	6	$d_c = \left(1.10 + 1.24\ \frac{r}{L}\right) \frac{P}{kL^2}$
Interior	W - '33	8	$d_i = (1 - Z)\ \frac{P}{8kL^2}$
Interior	W - '47	12	$d_i = \frac{P}{8kL^2} \left[1 - 0.183\ \frac{r^2}{L^2}\ (2 \log \frac{L}{r} - 0.117)\right]$
Edge	W - '47	14	$d_e = P\sqrt{\frac{2 + 1.20u}{Eh^3k}} \left[1 - (0.76 + 0.40u)\ \frac{r}{L}\right]$

W = H. M. Westergaard, K = E. F. Kelley, P = Gerald Pickett

P = Total load, lb., h = slab thickness, in., u = Poisson's ratio, E = Elastic modulus of concrete, psi, Z = deflection ratio, L_1 = Multiple of L, k = Subgrade modulus, pci, $L^4 = \frac{Eh^3}{12\ (1 - u^2)k}$, $B = \sqrt{1.6r^2 + h^2} - 0.675h$

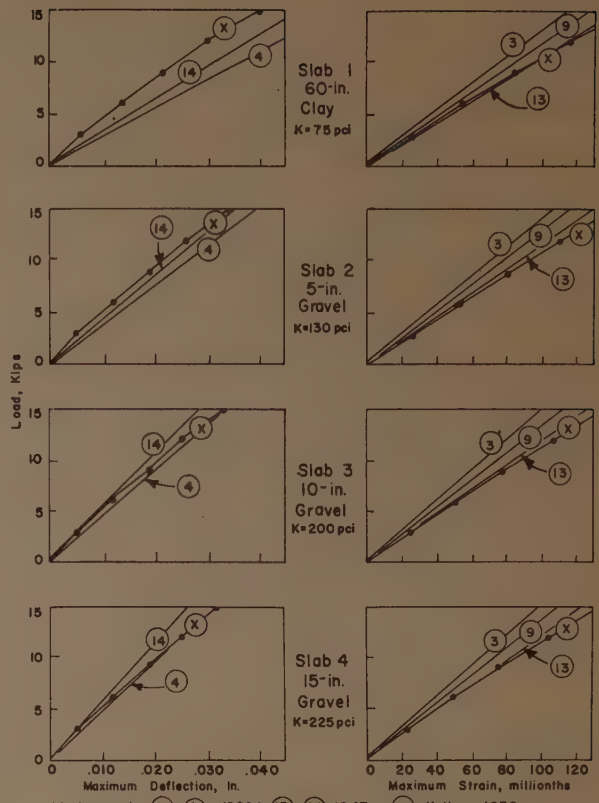
subbase. At the interior, a total reduction of 0.002 in. was accomplished by 15 in. of gravel; the 5-in. layer accounted for 0.001 in.

The study of effect of subbase thickness on strain showed that the reduction in slab strain per inch of subbase thickness is not significantly different for the 5-in. layer than it is for the thicker subbases. The greatest effect was found for free corner loading, where strains were reduced 15% by increasing the subbase thickness from 5 in. to 15 in.



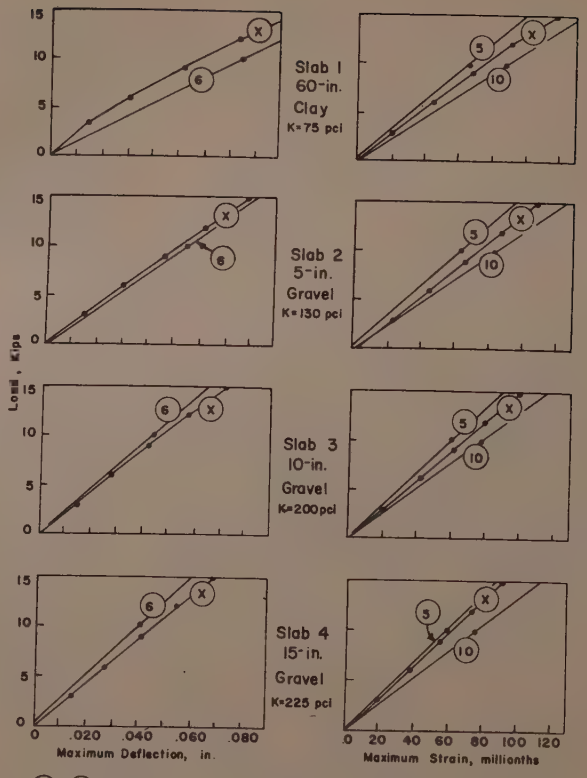
DEFLECTION AND STRAIN FOR INTERIOR LOADS

FIG. 13



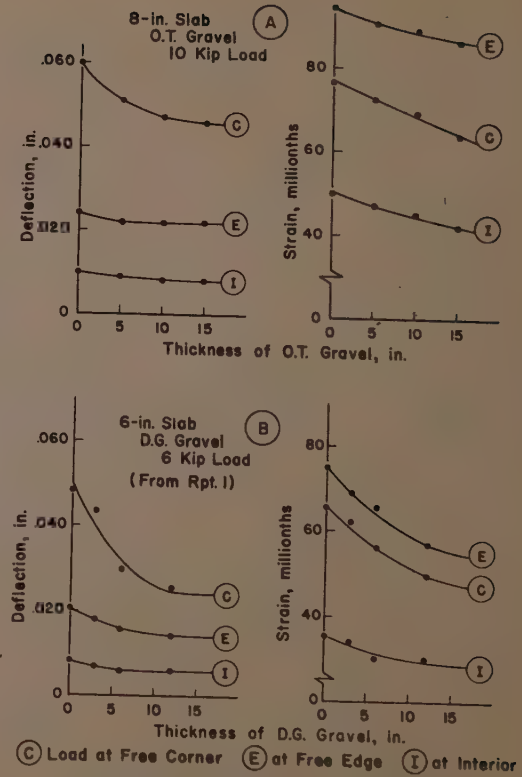
DEFLECTION AND STRAIN FOR EDGE LOADS

FIG. 14



DEFLECTION AND STRAIN FOR CORNER LOADS

FIG. 15



DEFLECTION AND STRAIN
VS SUBBASE THICKNESS

Fig. 16

Curves from tests[1] on 6-in. slabs on dense-graded subbases have been reproduced in Fig. 16B for thicknesses up to 15 in. Comparing the two sets of curves, A and B, it is seen that the 6-in. slabs on dense-graded sand and gravel are more sensitive to subbase structure than 8-in. slabs on open-graded sand and gravel, but the general effects of subbase thickness are similar.

Subbase Evaluation in Terms of Slab Thickness

It is important to know whether a road structure can be made adequate in resistance to deflection and strain, and more economical, by building thin slabs on thick subbases, or by building thick slabs on subbases of the minimum thicknesses required to prevent pumping. Although at this writing there is insufficient test data for complete experimental analysis, theory and experiment can be combined to evaluate various combinations of slab-subbase thickness.

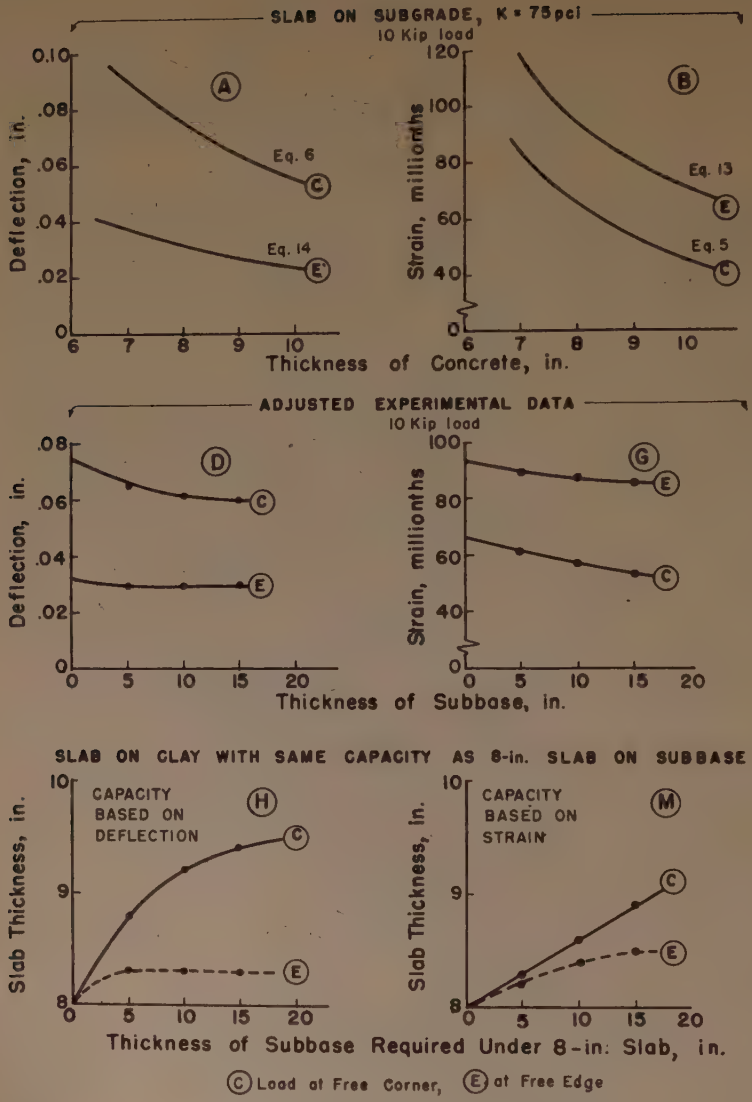
In Figs. 14 and 15, for corner and edge loading, it is seen that each experimental curve is in reasonable agreement with some theoretical curve. Therefore, by a combination of test data and theory, curves may be constructed from which one may find the thickness of slabs without subbases which will show the same deflections or strains as thinner slabs built upon various thicknesses of open-graded sand-and-gravel subbases. This method of analysis was used for the 6-in. slabs on dense-graded gravel reported earlier.

First, curves A and B, Fig. 17, were drawn relating free edge and free corner deflections and strains to slab thickness using theoretical equations 5, 6, 13 and 14 with P = 10,000 lb and k = 75 pci, the subgrade modulus for the clay subgrade. Next, the experimental data of Fig. 16 for zero subbase thickness were compared with the theoretical data. The experimental curves were then translated vertically to make the experimental and theoretical results coincide for the 8-in. slab on the clay subgrade. The translated curves are designated D and G. Now, to find the thickness of concrete on a clay foundation which will give deflections equal to those of the 8-in. slab on the subbase, select a subbase thickness in D, intersect the curve for load positions desired, and read the adjusted deflections. Enter A with this deflection, intersect the proper load-position curve, and read the resulting slab thickness. The procedure for equal strains is similar. A series of these operations produced curves H and M.

This method of evaluation leads to the following conclusions:

1. The subbase was most effective in the region of the free corner. In this region, 7-1/2 in. of gravel subbase would be needed to hold deflections of an 8-in. slab to the same values as those of a 9-in. slab on clay, whereas 17 in. of subbase would be required to hold strains of an 8-in. slab equal to those for a 9-in. slab on clay.

2. The gravel subbase was not particularly effective in reducing slab deflections or strains when loads were applied at the edge. Five inches of gravel under the 8-in. slab made it as effective as an 8.3-in. thick slab without subbase. No additional benefit was derived from thicker subbases. In the case of strains, 7 in. of subbase under an 8-in. slab made it as effective as an 8.3 in. thick slab without subbase, and 15 in. of subbase under an 8-in. slab made it as effective as an 8.5 in. slab without subbase.


SLAB ON SUBGRADE, K = 75 pci
10 Kip load
Deflection, in.
Strain, millionths
Eq. 6
Eq. 14
Eq. 13
Eq. 5
Thickness of Concrete, in.
ADJUSTED EXPERIMENTAL DATA
10 Kip load
Deflection, in.
Strain, millionths
Thickness of Subbase, in.
SLAB ON CLAY WITH SAME CAPACITY AS 8-in. SLAB ON SUBBASE
CAPACITY BASED ON DEFLECTION
CAPACITY BASED ON STRAIN
Slab Thickness, in.
Thickness of Subbase Required Under 8-in. Slab, in.
Ⓒ Load at Free Corner, Ⓔ at Free Edge

SUBBASE STRENGTH IN TERMS OF SLAB THICKNESS

Fig. 17

The minor contribution to strength of the road structure by open-graded gravel subbases thicker than 5 in. is corroborated later in the report (Fig. 24). It seems doubtful that it would be economical to use these subbases in thicknesses greater than that necessary for pumping and frost control.

Maximum Subbase and Subgrade Pressures

Pressures between the slab and subbase and between subbase and subgrade were measured with Carlson stress meters. Relations between pressure and applied load for various load positions are shown in Fig. 18.

In general, pressures between the slab and subbase increased with greater subbase thicknesses. Fig. 19A shows this trend for 12,000-lb loads. This effect was negligible at the interior of the slab but when the load was at the corner the pressures on the subbase increased approximately 1 psi for each inch of subbase thickness. However, as seen in Fig. 19B the pressures on the subgrade did not increase and in fact decreased as the subbase was increased from 5 to 15 in.

Since a 12-kip wheel load was used to plot the data of Fig. 19B, the pressures are likely to be slightly greater than those under 8-in. pavements under legal loads approximating 9 kips per wheel. Thus sub-grade pressures in the field under conditions similar to those of this test would be 5 to 6 psi at slab edges and doweled corners, and 2 to 3 psi at interior positions.

Pressure-Deflection Relations

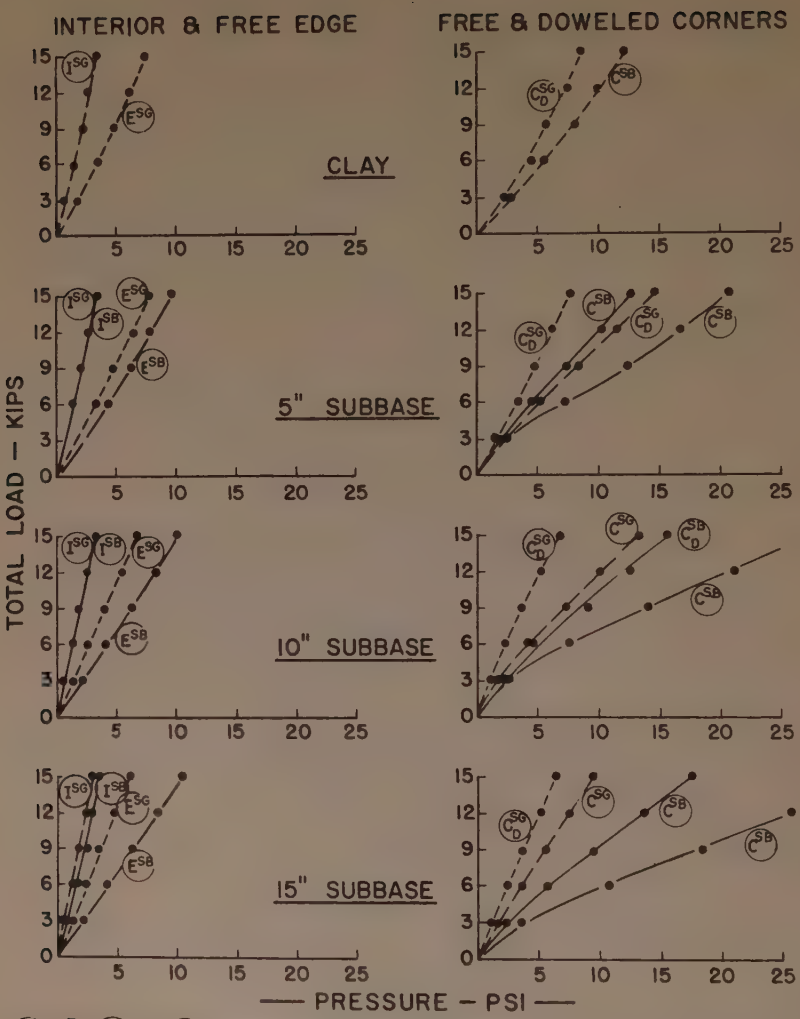
From the data of Figs. 9 and 18, pressure directly under the slab was plotted against deflection to produce Fig. 20. This relation has been studied(1) for 6-in. slabs on dense-graded gravel, and for those conditions the ratio of pressure to deflection was approximately a linear function of subbase thickness and was independent of load position. In the present case of 8-in. slabs on open-graded gravel, p/d appears to vary with load position as well as subbase thickness.

To compare p/d from slab test data with k from 30-in. plates, the ratios were read from Fig. 20 at deflection levels comparable to maximums found in highway tests, namely, 0.050 in. at corners, 0.025 in. at edges and 0.010 in. at interior positions. These values are compiled in Table 5. As in the previous study, p/d is always considerably greater than k. When p/d is used in place of k in the theoretical equations, there is no universal betterment of agreement between experimental and theoretical results. Equation 2 of Fig. 13 approaches the experimental curve for deflections of slab 1, but increases the deviation in slabs 2, 3, and 4. Eq. 4, Fig. 14, is a better match with experimental data when p/d is used, but Eq. 14 is poorer. There is some improvement in Eq. 6 for slabs 1 and 2 but a disadvantage in slabs 3 and 4.

Strain curves 1, 3, 5, 7, and 9 provide poorer agreement with experimental data when p/d is used instead of k with the 30-in. plate. However, the relation between the experimental curves and strain curves 10 and 13 are improved by the use of the p/d relationship. The conclusion is that k from the plate test is as good a foundation modulus to use in theoretical computations as any modifications that might be suggested from the p/d study.

Effect of Load Transfer Across Doweled Joint

Loads applied at a doweled edge or joint cause deflections, strains and pressures which depend upon the efficiency of the load transfer system. In

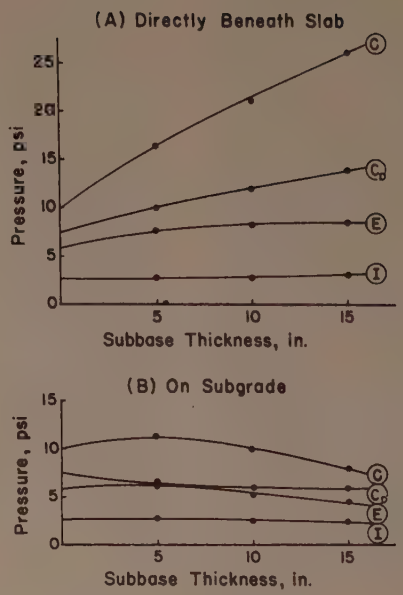


I^{SG} E^{SB} C^{SB} & C_D^{SB} Pressure Directly Beneath Slab Under Interior, Free Edge, Free Corner, and Doweled Corner Loads, Respectively

I^{SG} E^{SG} C^{SG} & C_D^{SG} Pressure On Clay — Beneath Subbase

MAXIMUM PRESSURES BENEATH SLAB AND SUBBASE

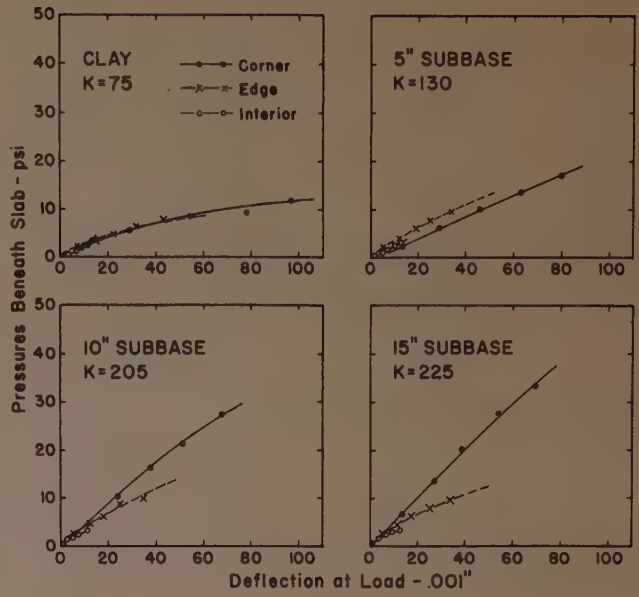
Fig. 18



Ⓒ Ⓒd Ⓔ Ⓘ-Load at Free Corner, Doweled Corner, Free Edge and Interior respectively

PRESSURES DUE TO 12-KIP LOAD

Fig. 19



PRESSURE-DEFLECTION RELATIONS AT POINT OF LOADING

Fig. 20

TABLE 5

PRESSURE-DEFLECTION RATIOS

	Ratio, pci			
	Clay Subgrade	Subbase Thickness 5 in.	10 in.	15 in.
k, 30-in. plate at 0.05 in.	75	130	205	225
p/d, Corner load at 0.05 in.	170	220	420	500
p/d, Edge load at 0.025 in.	220	300	460	500
p/d, Interior load at 0.010 in.	220	250	270	300

these tests the system was composed of 1-in. slip dowels at 18-in. centers through a 3/16-in. sheet metal separator. With an appraisal of the load transfer devices in mind, deflections, strains and pressures were measured on both sides of the joint during the static loading studies. Values on the loaded side were given in Fig. 10. Values on the opposite side of the joint were always less than those at the load, and the differences in deflections, pressures and surface strains across the joint at the 10-kip load level are shown in Fig. 21.

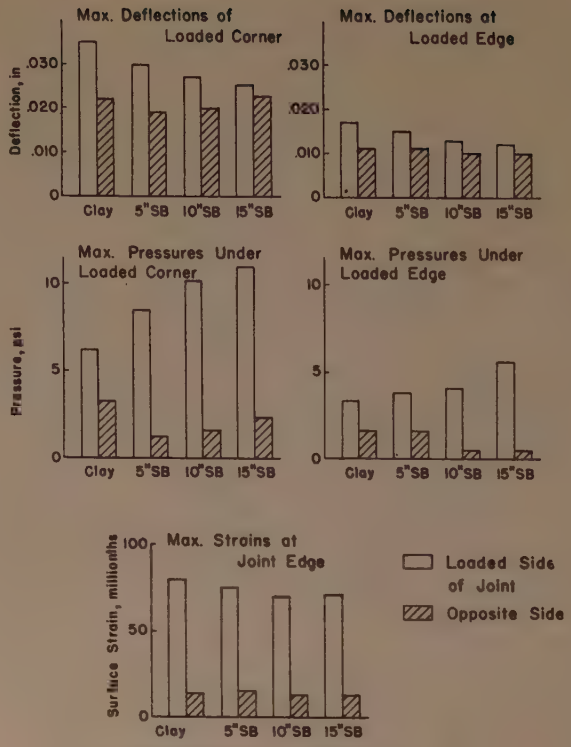
Due to instrumentation methods and limitations, it is believed that deflection measurements are more indicative of the effectiveness of the dowel system as a device for transferring load than measurements of pressure or surface strain. The pressure cell diameters are 7-1/4 in. and in order to reduce interference in operation, two adjacent cells at a joint are approximately 8 in. on centers. Thus, part of the pressure reduction indicated by two adjacent cells is due to lateral placement and part is due to the action of the joint.

Surface strains likewise do not indicate the true relationship between maximum stresses on opposite sides of a joint because the load on one side is applied through a distributing plate whereas that on the other is applied by the dowel. It is unlikely that the surface strains across the joint measured in this test are maximum strains in the concrete.

Performance Rating of Doweled Joint

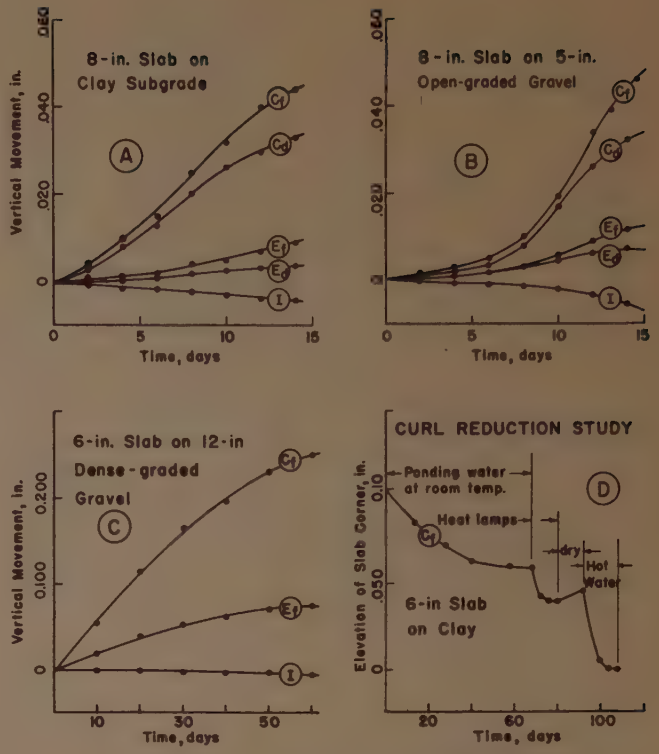
The best load-transfer device that could be built in a pavement joint is one in which half the applied load is transferred to the adjacent slab. Since deflection is proportional to load, this implies that when such a joint is loaded on one side the deflection of the loaded side equals that of the opposite side. Each deflection approximates one half that due to an application of this same load at the free edge.

An expression involving deflections d_i, d_e, and d_j due to a given load at an interior, free edge, and joint edge position may serve to indicate the



MEASUREMENTS AT DOWELED JOINT
10 KIP LOAD

Fig.21



C_f = Free Corner, C_d = Doweled Corner, E_f = Free Edge, E_d = Doweled Edge, I = Interior

SLAB CURLING

Fig.22

load-carrying capacity of the pavement at a joint relative to the capacity at an interior position. This rating is expressed as the "joint performance ratio"

$$R = \frac{d_e - d_j}{d_e - d_i}$$

which has the value 1 when $d_j = d_i$ and the value 0 when $d_j = d_e$. From Westergaard's formulas (Table 4) using $d_j = 1/2\ d_e$, it is found that R is independent of k and P, and has a maximum value of 0.70. Thus theoretically an "optimum" joint is a built-in weakness which reduces the load-carrying capacity of a pavement 30% below its capacity if the pavement were continuous and unbroken.

Methods for estimating joint "efficiency" and "effectiveness" have been proposed by several investigators. Effectiveness was computed by Teller and Sutherland(6) using the expressions:

$$E_1 = \frac{2d'_j}{d_j + d'_j} \quad \text{and} \quad E_2 = 2^{\left(\frac{d_e - d_j}{d_e}\right)}$$

where d_e and d_j have been defined, and d'_j is the deflection of the unloaded slab across the joint from the load. Efficiency was defined by Westergaard(5) by the symbol J such that

$$J = 1 - \frac{d_j - d'_j}{d_e - d'_e}$$

where d'_e is the deflection of the unloaded slab when no provision is made for load transfer.

Efficiency was also expressed by Teller and Sutherland as the stress ratio

$$E_3 = \frac{S_e - S_j}{S_e - S_i}$$

when S_e, S_j and S_i are maximum stresses due to loads at a free edge, joint edge and slab interior. This ratio evaluates the load transfer in terms of stresses, but interpretation is difficult because from the interior and edge equations of Table 4, S_i is approximately 2/3 S_e, and 100% efficiency is achieved when S_j = 2/3 S_e rather than 1/2 S_e which one would anticipate when each joint edge carries half the load.

The above expressions are evaluated for the test slabs in flat condition in Table 6.

The effect of increasing foundation capacity is apparent in all methods except E_3. This is consistent with previous data which show stresses to be less sensitive to k than deflections.

Tests on Curled Slabs

The test slabs were kept flat for the greater portion of the test program in order that slab shape and bearing area would not be variables which would complicate the analysis of subbase effect. However, the slabs were later

TABLE 6
Joint Performance and Load Transfer Ratings

Rating Symbol	Rating for Indicated Subbase Thickness, in. 0	5	10	15	Optimum Value ($d_j = 1/2\ d_e$)
R	0.46	0.48	0.55	0.76	0.70
E_1	0.78	0.84	0.84	0.87	1.00
E_2	0.57	0.60	0.67	0.75	1.00
J	0.74	0.82	0.82	0.85	1.00
E_3	0.40	0.34	0.40	0.37	1.00 ($S_j = 2/3S_e$)

permitted to curl so that the performance under load might approximate that of slabs in the field when the edges and corners are curled upward due to differential moisture content or temperature. The curl induced in the slabs was the result of drying shrinkage of the upper surface. Moisture gradient was not measured and no analysis was made of restraint stresses induced in the slab by subgrade and slab weight.

Magnitude of Curl

Corners and edges of slabs drying from the top curl upward and remain at elevated positions unless forced downward by load or temperature. In Fig. 22, graphs A and B show the upward movements of corners and edges of 8-in. slabs and downward movements of the slab centers. About two weeks after the ponding water was removed, the corners were elevated over 0.04 in. All of the 8-in. slabs behaved in similar fashion when dried from the top so only data for the slabs on the sub-grade and on a 5-in. subbase are given. The rate of curling was dependent upon the ambient humidity, but corner elevations of 0.05 in. were easily attained, and usually the slabs were load-tested when curled approximately this amount.

The rate of upward movement of the 6-in. slabs in the first study (graph C) was considerably greater than that of the 8-in. slabs, and the increased time span of the first test resulted in a final corner elevation of 0.25 in. as seen in Fig. 22C.

Graph D, from data on a 6-in. slab, shows that corner elevation cannot be restored by simply re-wetting the surface. At room temperature, surface water reduced the corner elevation about 40%, dry heat accomplished another 20% temporarily but the drying action soon reversed the trend. Finally, hot water brought the corners down to their initial elevations. At the cessation of this treatment, after water was removed, the slab corners again raised to elevation 0.100 in.

Load Tests

The test routine outlined for flat slabs was repeated on curled slabs. All slabs were tested with similarity in results. The complete data for the 8-in.

slab on 5-in. open-graded sand and gravel are shown in Fig. 23. Differences in magnitudes of measured quantities from those measured for flat slabs at various loads may be computed by comparing Fig. 23 with Figs. 9, 10 and 11. The differences for a 10,000-lb load are shown in Fig. 24.

Lines representing equations 6, 9, 10, 13 and 14 have been drawn in Fig. 23 for comparison with theory. Kelley's Eq. 9, Pickett's Eq. 10, and Westergaard's Eq. 13 and 14 were developed for curled slabs and the experimental data are in good agreement with these curves. Westergaard's Eq. 6 is an original flat-slab curve and is presented here because no corner deflection equation has been developed for curled slabs.

As seen in the lower part of Fig. 23, subbase pressures under the edge, were approximately proportional to the applied load, but the corners showed a delayed response to increasing load increments. The load-pressure curve for the free corner changes slope rather sharply at a 6-kip load. The corresponding deflection curve shows that the corner had deflected about 0.04 in. when the break in the pressure curve occurred. This is reasonable in view of the fact that the elevation of the curled corner was 0.035 in. and no direct pressure was applied over the subgrade cell until the curling had been overcome. It may also be seen at the top of Fig. 23 that the strains became less per load increment when subgrade contact was made at a load of about 6,000 lb.

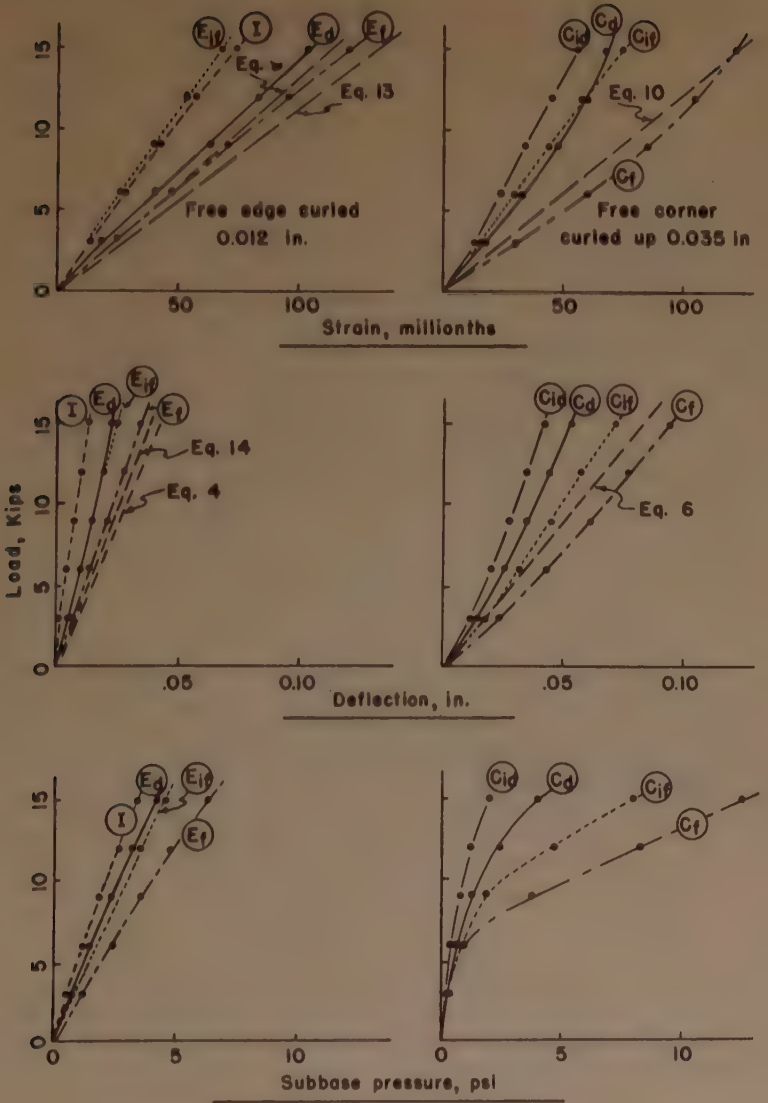
Since load-strain and deflection data for curled slabs on 0, 10, and 15 in. subbases were similar in character to those of Fig. 23 for a 5-in. subbase, a complete treatment of these data is omitted. A concept of the trends in strain and deflection magnitudes for slabs on other subbases may be had from Fig. 24 in which values are shown for a 10-kip load. For direct comparison, deflections and strains for flat slabs under the same loads are adjacent to the corresponding values for curled slabs.

It is seen that both free and doweled corners have considerably higher deflections and strains when curled than when flat. These differences vary considerably but it is not unusual to find curled-slab values 30 to 40 per cent above flat-slab values in these areas.

Edge deflections of curled slabs are slightly greater than those for flat slabs, and curled-slab edge strains are slightly less than flat-slab edge strains. This has been observed in other slab tests, both indoors and outdoors. The edge strains of curled slabs usually ranged from 5 to 15 per cent lower than the flat-slab values.

Effect of Load Position on Strain and Deflection

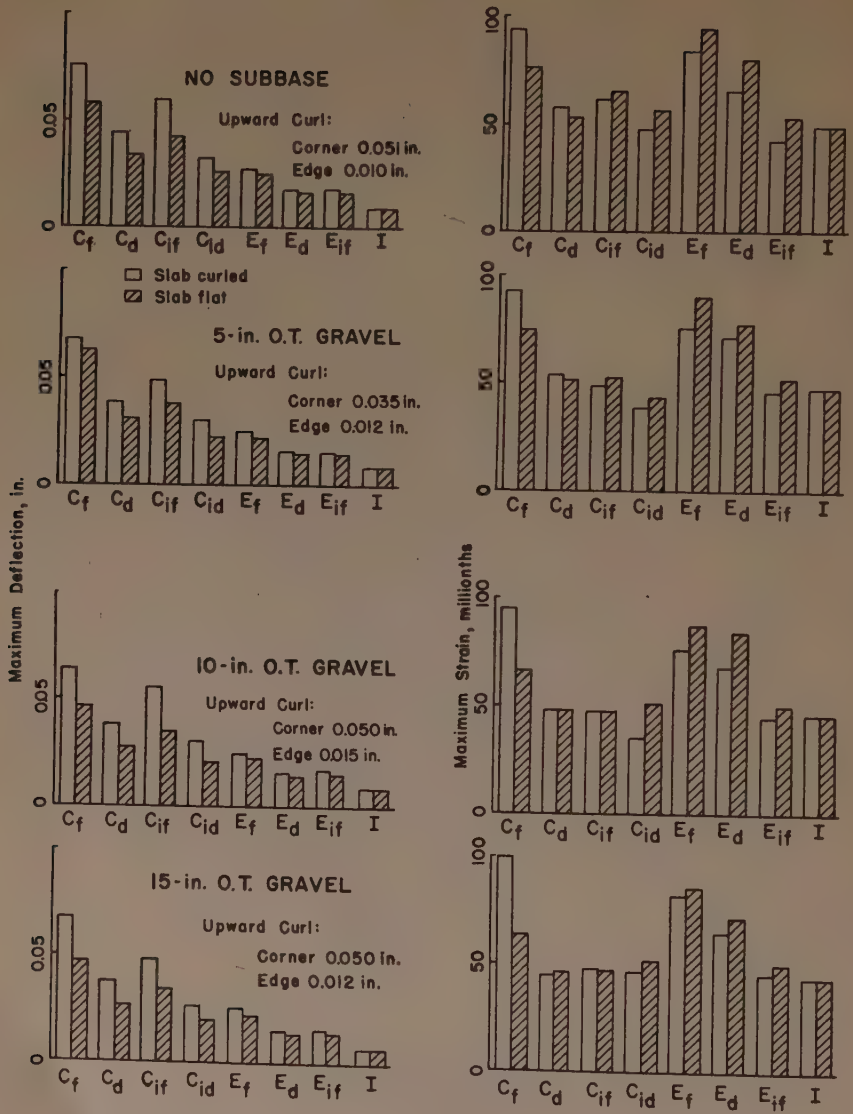
Fig. 24 clearly shows that for both flat and curled slabs, strains are higher near free corners, free edges and doweled edges, and deflections are high in the corner region. However, in all cases these relatively high strains and deflections can be greatly reduced by placing the load inward from the pavement edge. For example, in these tests, with the 12-in. load-plate seated one foot in from the edge (18 in. from center of plate to slab edge), corner and edge strains were held to values approximating those observed under interior loading. This is a very significant observation since current traffic surveys show that on present-day 12-ft wide traffic lanes, very few wheels travel within the outer foot of the pavement. Thus it becomes obvious that the wider pavements now being used not only contribute to safety, but also reduce pavement stresses due to load.



Load Position: I = Interior, E_f = Free Edge, E_{if} = Inward from Free Edge, E_d = Doweled Edge, C_f = Free Corner, C_{if} = Inward from Free Corner, C_d = Doweled Corner, C_{id} = Inward from Doweled Corner

Fig. 23 - STRAINS, DEFLECTIONS, AND PRESSURES FOR CURLED 8-IN. SLABS

5-in. Gravel Subbase



Load Position: I = Interior, E_f = Free Edge, E_{if} = Inward from Free Edge, E_d = Doweled Edge, C_f = Free Corner, C_{if} = Inward from Free Corner, C_d = Doweled Corner, C_{id} = Inward from Doweled Corner

10 kip load

Fig. 24 - DEFLECTIONS AND STRAINS IN FLAT AND CURLED SLABS

8-in. Slab

Only in one area do the strains remain relatively high regardless of the width of the pavement and the lateral position of the load. This is at a doweled edge, which may be considered also as a doweled transverse joint. Strains in this area will be evaluated more thoroughly in future studies.

SUMMARY AND CONCLUSIONS

Static loads were applied at different positions to a series of full-scale laboratory replicas of concrete roadway slabs to study the effect of thickness of open-textured sand and gravel subbases upon slab strains, deflections and pressures. Comparable tests were made when the slabs were kept flat to reduce the variables in the subbase study, and when the slabs were curled upward to simulate the prevailing shape of slabs as they exist in highways. For the condition of this study the following conclusions may be drawn.

Effect of Subbase Thickness on Load Capacity

The open-graded sand and gravel subbases under flat slabs were effective in reducing free-corner strains and deflections. Computations based on the test data and on the best fitting theoretical treatment showed that the free-corner deflection of an 8-in. slab on a 7-1/2 in. subbase would be about equal to that of a 9-in. slab directly on the subgrade. To accomplish a similar equivalence in corner strains, the 8-in. slab needed 17 in. of subbase. Edge load tests indicated that the subbases were less effective in reducing strains and deflections at this position than at the free corner (Fig. 17), and a 15-in. subbase had little advantage over a 5-in. subbase. These results show that unless thick subbases are required for frost control, the slight structural advantage of thick open-graded subbases could usually be achieved more economically by thickening the concrete. Generally, in frost-free areas the optimum subbase thickness is the 3 to 6 inches required to prevent pumping.

Comparing these results with those from a previous study on dense-graded sand and gravel subbases, it is seen that open-graded subbases under 8-in. slabs were less effective in deflection and strain reduction than the dense-graded subbases under 6-in. slabs.

Pressures on Subbase and Subgrade

The interface pressures between slab and subbase increased as the subbase thickness increased. However, pressures were distributed through the subbase layer in such a manner as to reduce the pressure on the subgrade slightly when subbase thickness was increased (Fig. 19). The tests indicate that the pressures on the subgrade in the field under an 8-in. slab on a granular subbase will be of the order of 5 or 6 psi at slab edges and doweled corners, and 2 or 3 psi at interior positions when the slabs are flat. Pressures under edges decreased when the slab was curled upward.

Effect of Load Position and Dowels on Strain and Deflection

Strains at slab edges and at free corners were greatly reduced when the load was applied inward from the slab edge. Dowels at joints also were effective in the reduction of strains in the corner region (Figs. 12 and 24). For a load one foot in from the edge, the strains at the edge or at a doweled corner

or a free corner were practically equal to those for a load at the interior of the slab. These observations on both flat and curled slabs are significant and show the importance of consideration of load position when calculating the effect of load repetitions in design of a concrete pavement.

Deflections at the corner were greatly reduced when the load was applied inward from the free edge of the slab. However, dowels at the joint were even more effective in reducing corner deflection than was the inward load position. A combination of dowels and inward loading gave corner deflections approximately as low as those observed when the load was applied at a free edge. (Figs. 12 and 24). When the slabs were curled, deflections due to corner loads were as much as 25 percent greater than for flat slabs. However, deflections for free edge loading were not significantly greater for curled slabs than for flat slabs.

Again, as in the case of strains, loads inward from the free edge of both flat and curled slabs developed edge deflections much smaller than those caused by loads at the edge. These reduced deflections prolong pavement life by reducing possible subbase densification and subgrade pumping where native pumping-susceptible materials are used.

Comparison of Experimental Results with Theory

Strains and deflections measured under interior loading were found to be slightly greater than those computed by theory. However, both Westergaard's original 1926 equations (1 and 2) and his 1947 equations (11 and 12) agree reasonably well with experimental results and may be used with confidence. His 1933 equations (7 and 8) do not fit the experimental data (Fig. 13).

At the free edge, experimental strains approximated Westergaard's 1947 equation (13) when slabs were flat, and Kelley's 1939 equation (9) when slabs were curled. However, as the strains at the edge are not greatly different for flat and curled slabs, equation (13) also checks edge strains for curled slabs (Fig. 14 and 23). Experimental deflections were less than theoretical for slabs directly on the clay subgrade and on the 5-in. subbase, but fell between Westergaard's 1926 and 1947 equations (4 and 14) for the thicker subbases.

Corner strains and deflections for flat slabs were in rather good agreement with Westergaard's 1926 equations (5 and 6), (Fig. 15). For curled slabs, however, experimental corner strains checked best with Pickett's 1946 equation (10), (Fig. 23).

Summary of Principal Findings

1. The first 5-in. thickness of open-graded granular subbase contributed more to the load capacity of a pavement than any subsequent 5-in. layer. At free corners where the subbase was most effective, an increase of 1 in. in slab thickness developed the same resistance to deflection as 7-1/2 in. of subbase. For developing the same resistance to strains, 17 in. of subbase was equivalent to 1 in. increase in slab thickness. A recommendation of 3 to 6 in. of open-graded subbase over pumping-susceptible soils in preference to thick subbase appears to be good structural practice when frost control is not a consideration.

2. Pressures on subgrades under 8-in. concrete slabs were rather insensitive to thickness of open-graded subbase and were of low magnitude, varying

from 2 to 3 psi at interior positions to 5 to 6 psi at edges when loads were comparable to those produced by highway truck traffic.

3. The appreciable reduction in edge stresses and deflections resulting from placing the load inward from the extreme edge suggests that, in addition to other advantages, wide traffic lanes, with a consequent reduction of wheel passes on the slab edge, contribute to extended pavement life. This factor should be evaluated for pavement design.

4. These tests indicate that the most practical formulas for the computation of stresses and deflections in concrete pavements due to loads are Westergaard's original 1926 equations for interior loads, his 1947 equations for edge loads, and Pickett's 1946 equation for stresses due to corner loads. Values computed by the 1933 equations are not corroborated by experiment.

BIBLIOGRAPHY

1. Childs, L. D., Colley, B. E., and Kapernick, J. W. — Tests to Evaluate Concrete Pavement Subbases. Journal of the Highway Division, Proceedings of the American Society of Civil Engineers, Vol. 83, HW 3, July 1957.

2. Westergaard, H. M. — Stresses in Concrete Pavements by Theoretical Analysis. Proceedings, Highway Research Board Vol. 5 p 90, 1925, Public Roads, Vol. 7, No. 2 p 25, April 1926.

3. Kelley, E. F. — Application of the Results of Research to the Structural Design of Concrete Pavement. Public Roads, Vol. 20, No. 5, p 83, July 1939.

4. Pickett, Gerald — A Study of Stresses on the Corner Region of Concrete Pavement Slabs Under Large Corner Loads. Concrete Pavement Design. Portland Cement Association, Chicago 1946. (1951 Edition p 77)

5. Westergaard, H. M. — New Formulas for Stresses in Concrete Pavements of Airfields. Proceedings, American Society of Civil Engineers, Vol. 73 pp 690-692.

6. Teller, L. W. and Sutherland, Earl C. — A Study of the Structural Action of Several Types of Transverse and Longitudinal Joint Design. Public Roads, Vol. 17 No. 7, pp 93-94, Sept. 1936.

D8 —"Resurfacing and Patching Concrete Pavement with Bonded Concrete," by EARL J. FELT.
Reprinted from *Proceedings of the Highway Research Board*, 35 (1956).

D9 —"Review of Data on Effect of Speed in Mechanical Testing of Concrete," by DOUGLAS MCHENRY and J. J. SHIDELER.
Reprinted from *Special Technical Publication No. 185*, published by American Society For Testing Materials (1956).

D10—"Laboratory Investigation of Rigid Frame Failure," by R. C. ELSTNER and E. HOGNESTAD.
Reprinted from *Journal of the American Concrete Institute* (January, 1957); *Proceedings*, 53, 637 (1957).

D11—"Tests to Evaluate Concrete Pavement Subbases," by L. D. CHILDS, B. E. COLLEY and J. W. KAPERNICK.
Reprinted from the *Journal of the Highway Division, Proceedings of the American Society of Civil Engineers, Proc. Paper No. 1297*, Vol. 83, HW3, July, 1957.

D12—"Ultimate Strength of Reinforced Concrete in American Design Practice," by E. HOGNESTAD.
Reprinted from *Proceedings of a Symposium on the Strength of Concrete Structures*, London, May, 1956.

D13—"Effect of Variations in Curing and Drying on the Physical Properties of Concrete Masonry Units," by WILLIAM H. KUENNING and C. C. CARLSON.
Published by Portland Cement Association, Research and Development Laboratories, Chicago, Illinois, November, 1956.

D14—"Lightweight Aggregates for Concrete Masonry Units," by C. C. CARLSON.
Reprinted from *Journal of the American Concrete Institute* (November, 1956); *Proceedings*, 53, 491 (1956).

D15—"Confirmation of Inelastic Stress Distribution in Concrete," by EIVIND HOGNESTAD.
Reprinted from the *Journal of the Structural Division, Proceedings of the American Society of Civil Engineers, Proc. Paper 1189*, Vol. 83, No. ST 2, March, 1957.

D16—"Strength and Elastic Properties of Compacted Soil-Cement Mixtures," by EARL J. FELT and MELVIN S. ABRAMS.
Reprinted from *Special Technical Publication No. 206*, published by the American Society for Testing Materials (1957).

D17—"Lightweight Aggregate Concrete for Structural Use," by J. J. SHIDELER.
Reprinted from *Journal of the American Concrete Institute* (October, 1957); *Proceedings*, 54, 299 (1957).

D18—"Stresses in Centrally Loaded Deep Beams," by P. H. KAAR.
Reprinted from *Proceedings of the Society for Experimental Stress Analysis*, Vol. 15, No. 1, 77 (1957).

D19—"Strength of Concrete Under Combined Tensile and Compressive Stresses," by DOUGLAS MCHENRY and JOSEPH KARNI.
Reprinted from *Journal of the American Concrete Institute* (April, 1958); *Proceedings*, 54, 829 (1958).

D20—"General Considerations of Cracking in Concrete Masonry Walls and Means for Minimizing It," by CARL A. MENZEL.
Published by Portland Cement Association, Research and Development Laboratories, Chicago, Illinois, September, 1958.

Continued on Outside Back Cover

D21—"Tests of Concrete Pavements on Gravel Subbases," by L. D. CHILDS and J. W. KAPERNICK.

Reprinted from the *Journal of the Highway Division, Proceedings of the American Society of Civil Engineers, Proc. Paper 1800*, Vol. 84, HW3, October, 1958.